The causes of geomagnetic storms during solar maximum

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Solar Phenomena

One of the oldest mysteries in geomagnetism is the linkage between solar and geomagnetic activity. The 11-year cycles of both the numbers of sunspots and Earth geomagnetic storms were first noted by *Sabine* [1852]. A few years later, speculation on a causal relationship between flares (~~see~~ Rust) and storms arose when *Carrington* [1859] reported that a large magnetic storm followed the great September 1859 solar flare. However, it was not until this century that a well-accepted statistical survey on large solar flares and geomagnetic storms was performed [*Newton*, 1943], and a significant correlation between flares and geomagnetic storms was noted. this issue

Although the two phenomena, one on the Sun and the other on the Earth, were statistically correlated, the exact physical linkage was still an unknown at this time. Various hypotheses were proposed, but it was not until interplanetary spacecraft measurements were available that a high-speed plasma stream rich in helium was associated with an intense solar flare [*Hirshberg et al.*, 1970]. The velocity of the solar wind increased just prior to and during the helium passage, identifying the solar ejecta for the first time (Goldstein). this issue Space plasma measurements and Skylab's coronagraph images of coronal mass ejections (CMEs) from the Sun firmly established the plasma link between the Sun and the Earth ~~[Gosling et al., 1976]~~. One phenomenon associated with magnetic storms is brilliant "blood" red auroras, as shown in Figure 1.

Fig. 1

Types of Solar Wind

Since the early 1960's, plasma and magnetic field instruments onboard interplanetary spacecraft have shown that a continuous flow of plasma comes outward from the Sun. At 1 Astronomical Unit (the Earth's distance from the Sun), this "solar wind" has a nominal velocity of ~400 km s^{-1} and a density of ~~~10~~ 7 particles cm^{-3}. The plasma consists of primarily hot electrons and protons with a minor fraction (~3–5%) of He^{++} ions. The plasma has an embedded magnetic field of intensity ~5 nT (nanoTesla). X

Besides the quiescent solar wind discussed above, near solar maximum (maximum number of sunspots), high-speed streams with velocities greater than 600 km s^{-1} and sometimes even greater than 1000 km s^{-1} occur occasionally. Using Newton's 1943 statistics, we know that approximately 90% of these high-speed streams at solar maximum are associated with CMEs. Because the ~~ambient~~ magnetosonic wave speed is only

~100 km s^{-1}, the difference in flow velocity between the faster stream and the slower stream is greater than the magnetosonic (fast-mode) speed. Thus, a fast forward shock is formed at the leading edge of the high-speed stream.

The shock is the outermost (antisunward) extension of the solar disturbance's propagation into interplanetary space. The region immediately behind (sunward of) the shock is composed of swept-up, compressed, and accelerated plasma and fields from the "slow" stream and is called the "sheath" region. Behind this is the driver-gas (CME) proper. The driver gas has previously been identified by a variety of signatures: Enhanced helium/hydrogen density ratios, low ion temperatures, or high-intensity magnetic fields with low variances and bidirectional streaming of ions and electrons. However, it should be mentioned that no one measurement or combination of measurements has proved to be a perfect means of identification ~~[*Zwickl et al.*, 1983; *Choe et al.*, 1992]~~, and intense research in this area is still ongoing.

Because of the typically high-intensity magnetic fields and low plasma temperatures, the driver gas is a low-beta plasma, β = 0.03–0.8, ~~[*Choe et al.*, 1992]~~. In about 10% of the cases, the magnetic field in these regions has an unusual configuration, with large out-of-the ecliptic components (see Figure 2; ~~[*Marubashi* [1986]~~). This magnetic field structure has been named a magnetic cloud [*Klein and Burlaga*, 1982]. When crossing the cloud, the field rotates from north-to-south or south-to-north with a time scale of a day or longer. This configuration is believed to be force-free, supported only by field-aligned currents flowing inside of it.

Fig. 2

Magnetic Reconnection and Magnetic Storms

The high-speed plasma events, which are led by shocks, followed by plasma sheaths and then by the driver gases, do not have direct access to the Earth~~'s dayside atmosphere and~~ ionosphere (~~see~~ Richmond). The protective magnetosphere (~~see~~ Cowley), which is created by the internal magnetic field of the Earth, deflects the interplanetary plasma and fields, so the latter flow around the magnetosphere. The solar wind plasma primarily enters the magnetosphere through magnetic connection between the interplanetary magnetic fields and the Earth's outer fields, as shown in Figure 3. When the interplanetary magnetic field (IMF) has a direction opposite (southward) to the magnetospheric fields (northward), interconnection can take place, and the solar wind convects these fields back into the tail region where they reconnect once more [*Dungey*, 1961; ~~*Vasyliunas*~~, 1975]. The magnetic tension on the freshly reconnected tail fields "snaps" the reconnected fields and plasma forward toward the nightside of the Earth. The convection process, through conservation of the first two adiabatic invariants (μ and $\oint p ds$), energizes the plasma. When the magnetic dayside connection is particularly intense, the nightside reconnection is also correspondingly high, and the plasma is driven deep into the nightside inner magnetosphere. Because the plasma is anisotropically heated by this process, plasma instabilities (loss-cone instabilities) (~~see~~ Gary) occur, creating electromagnetic and electrostatic plasma waves, which cyclotron resonate with the energetic

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Fig. 3

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particles ~~[Kennel and Petschek, 1966]~~. The wave-particle interactions break the particles' first adiabatic invariant, scattering them in pitch angle. Particles that have their mirror points lowered to altitudes at atmosphere/ionosphere heights are lost by collisions with atmospheric/ionospheric particles. In the loss process, atmospheric/ionospheric atoms and molecules are excited, resulting in characteristic auroral emissions (~~see~~ Akasofu). The above scenario is the cause of the diffuse aurora, a phenomenon that occurs primarily in the Earth's midnight sector. The spreading of the aurora toward local dawn is caused by electron azimuthal drift [Cowley, ~~Thissel~~]. This issue

As the energetic particles are convected deep into the Earth's nightside magnetosphere, they are also subjected to forces due to the magnetic field's curvature and gradient as well as forces due to particle gyration effects. For the same charge sign, these forces act in unison, with the net effect of protons drifting from midnight toward dusk and electrons from midnight toward dawn. This oppositely directed drift comprises a ring of current around the Earth. The current is a diamagnetic one, decreasing the intensity of the Earth's field. An enhanced ring current is the prime indicator of a magnetic storm. The total energy of the particles in the ring current (measured by the intensity of the diamagnetic field perturbation) is a measure of the storm intensity ~~[Dessler and Parker, 1959]~~.

We now compare the interplanetary features discussed previously and their relationships to the phases of a magnetic storm, shown in Figure 4, where the ordinate (the field averaged over these ground-based stations near the equator) gives the change in the horizontal component of the Earth's magnetic field and the abscissa gives time. As indicated in the figure, there are three phases to a geomagnetic storm—the initial phase, where the horizontal component increases to positive values of up to tens of nanoTeslas; a main phase that can have magnitudes of minus hundreds of nanoTeslas; and a recovery phase, where the field gradually returns to the ambient level. The time scales of the three phases are variable. The initial phase can last minutes to many hours, the main phase a half-hour to several hours, and the recovery from tens of hours to a week.

Fig. 4

An Interplanetary Example

Previously, we showed that a flux-rope configuration could lead to large southward field orientations, magnetic connection at the Earth's magnetosphere (when the IMF is southward), and aurora.

It should be noted that in the sheath and the driver gas, two regions where intense southward interplanetary magnetic fields can occur within high-speed streams, the field orientation has been found empirically to be northward directed with equal probability as southward orientations ~~[Gonzalez and Tsurutani, 1987]~~. There are also cases where the field lies primarily in the ecliptic plane and cases with large north-south components that vary rapidly in time. The latter cases do not cause storms because of their short reconnection/convection time scales. Therefore, only one in about six cases of CMEs that impinge upon the Earth leads to an intense ($D_{ST} < -100$ nT) magnetic storm ~~[Tsurutani and Gonzalez, 1990]~~. The above-mentioned driver gas fields apply to storms that occur at or near solar maximum, while less is known about possible equivalent structures during solar minimum.

Many of the solar wind-magnetic storm relationships discussed above can be illustrated by space plasma data, as shown in Figure 5. From top to bottom, the panels give the solar wind velocity, plasma density, magnetic field magnitude, two components of the magnetic field in Geocentric Solar Ecliptic (GSE) coordinates, the Auroral Electrojet index (AE) and D_{ST}. The auroral electrojet is an ionospheric current that flows at ~100-km altitude and is typically located at auroral latitudes (~63–68° magnetic latitude). The location moves equatorward during magnetic storms. This current becomes particularly intense during active auroral displays and can reach amplitudes of up to 10^7 Amperes. The AE index is a ground-based measurement of the magnetic field associated with this current. Fig. 5 ?

Using the ISEE-3 observations, *Gonzalez and Tsurutani* [1987] found that the ten intense storms (DST < −100 nT) during August 1978–December 1979 were associated with large-intensity (< −10 nT) and long-duration (> 3 hours) negative B_z events, of the type shown in Figure 5. D_{ST}

The recovery phase of the storm seen in Figure 5 is exceptionally long. Continuous auroral activity is associated with this interval and is illustrated by the bar in the AE panel. During this time, the interplanetary medium is characterized by rapid fluctuations in the transverse (y and z) components of the magnetic field. The field magnitude is relatively constant. Analyses of the field and plasma data indicate that these fluctuations are Alfvén waves [*Belcher and Davis*, 1971] propagating outward from the Sun. Use of magnetic field measurements on spacecraft closer to the Earth has demonstrated that the AE increases are correlated with southward deviations of the field, the latter associated with the Alfvén waves. Thus, the AE activity is due to magnetic reconnection [*Tsurutani et al.*, 1990]. However, it is noted that there is very little ring current activity (D_{ST}) during this extended interval.

The lack of ring current activity can be understood by the nature of the southward field components of the Alfvén waves. The fields are less intense than those during the storm main phase (see Figure 5), and their durations are considerably shorter. Thus, the consequential nightside convection will be of lower velocity and will occur sporadically. Plasma will be brought only into the outer regions of the magnetosphere where they feed the high-latitude aurora and not deep into the magnetosphere where the ring current predominantly resides ~~[Gonzalez et al., 1994]~~. Stet

Other types of solar wind-magnetospheric interactions, such as a "viscous interaction" between the solar wind and the magnetosphere [*Axford and Hines*, 1961], have been hypothesized. Evidence indicates that the Kelvin Helmholz instability occurs when the IMF is orthogonal (northward) to the tail field direction; however, it was recently shown that only ~0.1% of the solar wind ram energy enters the magnetosphere during these events, compared to 10% during magnetic reconnection intervals (storm events) ~~[Tsurutani et al., 1992]~~.

Future Space Physics Missions

Where do we go from here? How are we going to fully understand the flow of energy from the Sun to the magnetosphere and the eventual sinks in the ionosphere and magnetotail? The future space mission, the International Solar Terrestrial Physics (ISTP) mission, is devoted to quantitatively solving the energy flow problem discussed in this paper. Scientists from NASA, the European Space Agency, the Russian Space Research Institute, and the Japanese Institute of Space and Astronautical Science will do this energy mapping by placing spacecraft in interplanetary space (WIND, SOHO, and Cluster), in the magnetosphere (Polar and Cluster), and in the tail (GEOTAIL).

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Figure 1. The red aurora created by the emission of 6300 Å oxygen line at very high altitudes (200–600 km) where the collisional de-excitation time scales are larger than the metastable decay time of ~200 s. Courtesy of V. Hessler, Geophysical Institute, University of Alaska, Fairbanks. One thought [*Cornwall et al.*, 1971] is that the electromagnetic ion cyclotron waves generated by the loss cone instability of the ring current protons get damped and accelerate magnetosphere thermal electrons up to energies of ~2–3 eV. These low-energy electrons get stopped high in the atmosphere resulting in the aurora. Another possibility [*Fok et al.*, 1991] is that ring current ions and electrons are slowed down by Coulomb interactions with thermal plasma and are eventually removed from trapped orbits. There is now more evidence supporting this second mechanism.

Figure 2. A possible configuration of the magnetic fields within the low beta portion of the driver gas. ~~Taken from *Marubashi* [1986].~~

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Figure 4. The three phases of a magnetic storm.

Figure 5. An example of a solar flare-related high-speed interplanetary stream and its geomagnetic effects. Taken from *Tsurutani et al.* [1988]. An interplanetary shock is noted in the figure at the beginning of August 27 by an abrupt jump in the solar wind velocity, density, and magnetic field magnitude. The increase in ram pressure leads to an increase in D_{ST} to positive values, and is the onset of the storm initial phase. Toward the end of the day, B_z turns negative (southward) and remains in this direction for over 12 hours. D_{ST} decreases in response, signifying the start of the storm main phase, that is, the ring current build-up. As the IMF B_z turns positive (northward), D_{ST} begins to increase, and the onset of the recovery phase begins.

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